

**Major effusive eruptions and recent lava fountains :
Balance between expected and erupted magma volumes at Etna volcano**

Bonaccorso A. and Calvari S.

Istituto Nazionale di Geofisica e Vulcanologia
Sezione di Catania - Osservatorio Etneo
Piazza Roma 2, 95125 Catania, Italy

Corresponding author : Alessandro Bonaccorso email: bonaccorso@ct.ingv.it

Revision 2 : revision of resubmitted version

Geophysical Research Letters

November, 2013

This article has been accepted for publication and undergone full peer review but has not been through the copyediting, typesetting, pagination and proofreading process which may lead to differences between this version and the Version of Record. Please cite this article as doi: 10.1002/2013GL058291

Abstract

Over the last four decades Etna has shown a high output rate through numerous eruptions. The volcano has displayed two eruptive behaviors. The first is characterized by effusive eruptions that efficiently drained the storage system and emitted large volumes of magma, the second behavior is related to lava fountains, erupting small magma batches, which are normally with high frequency and have been considered as precursors of major effusive eruptions. In this paper, we present an updated estimation of emitted volumes from Etna eruptions, which include the 38 lava fountain episodes that occurred from January 2011 to April 2013. These recent explosive episodes have been frequent, discharging significant magma volumes. Observing the steady trend of magma output over time, we present insights on expected erupted volumes. We highlight that the January 2011 – April 2013 lava fountains, efficiently drained the intermediate-shallow storage system and favored a balance between the incoming and outgoing magma.

Key points

Etna volcano, effusive eruptions, lava fountains, erupted volumes

Key words

- Upgraded data base of the volumes emitted by the Etna eruptions
- Relations between erupted volumes and volcano equilibrium state
- Tool to evaluate the current state of the volcano and short term prediction

Index Terms

8414 - eruption mechanisms

8419 - volcano monitoring

8488 - volcanic hazard and risk

1. Introduction

Many of the major recent effusive eruptions at Mt. Etna, such as those that occurred in 1999, 2001, 2002-03, and 2008-09 [e.g., *Calvari et al.*, 2001; *Harris and Neri*, 2002; *Andronico et al.*, 2005; *Bonaccorso et al.*, 2011a], have been preceded by periods characterized by several lava fountaining episodes. In particular, during the last two decades the explosive episodes have been well-documented. Each of the several 1999 effusive eruptions from Bocca Nuova summit crater (BN), that occurred between 17 October and 5 November, as well as the February to November 1999 effusive eruption from the South-East Crater (SEC), were preceded by lava fountains [*Harris and Neri*, 2002; *Calvari et al.*, 2003]. During 2000, up to 66 lava fountain episodes were observed [e.g., *Andronico and Corsaro*, 2011], and 15 additional events occurred in the first half of 2001 [*Behncke and Neri*, 2003]. All these explosive episodes have been considered as precursors of the volumetrically more important effusive eruptions that took place in 2001 and 2002-03 [e.g., *Behncke and Neri*, 2003]. More recent examples of lava fountains preceding a flank eruption were the 7 events in 2007-08 preceding the 2008-09 major effusive eruption [*Andronico et al.*, 2008; *Bonaccorso et al.*, 2011a]. After the end of this last major eruption, between January 2011 and April 2013, there were as many as 38 lava fountain episodes [*Calvari et al.*, 2011; *Bonaccorso et al.*, 2011b, 2013a; *Ganci et al.*, 2012; *Gouhier et al.*, 2012], this time emitting much more magma than in the previous phases. Thus, an important question arose to see if these episodes were heralding an impending major effusive eruption or not. In this paper we evaluate recent data and highlight novel considerations that might help unravel Etna's recent eruptive activity, and possibly also predict the short-term future behavior of the volcano in terms of expected volumes of magma. We base our insights on the analysis of an extended database of Etna erupted volumes [*Allard et al.*, 2006; *Tanguy et al.*, 2007; *Harris et al.*, 2011, 2012], that we have updated, taking into account the volumes of lava flows and pyroclastics produced during the 38 lava fountains from January 2011 to April 2013. We discuss the average magma output rate to infer the volcano's future behavior in

terms of expected erupted volumes.

2. Lava fountain episodes in 2011-13

Several of the 38 eruptive episodes that took place between January 2011 and April 2013 have already been described, and their output quantified from ground measurements [e.g., *Calvari et al.*, 2011] and/or from satellite data [e.g., *Ganci et al.*, 2012; *Gouhier et al.*, 2012; *Bonaccorso et al.*, 2013a]. In general, the episodes started with increasing strombolian explosions, evolving to lava fountains, sustained eruptive columns, ash plumes, and lava flows. The average duration of these events was about three hours. The episodes were grouped in two phases: 25 lava fountains that took place from January 2011 to April 2012 and, after a 10-month pause, a further 13 episodes from February to April 2013. It is interesting to note that all the lava fountains episodes had similar main characteristics, with the height of the lava fountain being $\sim 300\text{-}600$ m, ash columns reaching $\sim 5\text{-}6$ km, and associated $\sim 4\text{-}5$ km long lava flows descending the Valle del Bove depression on the E flank of the volcano.

Ganci et al. [2012] calculated the effused lava volumes of the first 19 episodes that occurred from 12 January 2011 to 5 January 2012 by using a thermal satellite technique. For 7 episodes the volumes of the emitted lava were not retrieved because of cloud cover and/or ash interference with the satellite view. The average lava flow volume from the 12 robustly measured events is $1.75 \times 10^6 \text{ m}^3$, with a 25% deviation error of $0.44 \times 10^6 \text{ m}^3$.

The 25 lava fountains of the 2011-2012 first phase also ejected pyroclastic products that formed a 200 m high cone on the eastern flank of the SEC. A comparison of photographs and GPS surveys indicated a volume of $17 \times 10^6 \text{ m}^3$ for this pyroclastic deposit [*Behncke et al.*, 2012], with a 15% estimated error [*B. Behncke*, pers. comm.]. This implies a mean volumetric contribution of $0.7 \times 10^6 \text{ m}^3$ of pyroclastics for each lava fountain event. The representative mean total volume for each lava fountain episode (pyroclastics plus lava flows) is estimated at $2.5 \times 10^6 \text{ m}^3 \pm 30\%$.

The similarity of these episodes was also confirmed by the associated strain recorded by the two deep borehole strainmeters recently installed in the western flank of the volcano. For each lava fountain, these high precision instruments recorded almost identical changes, with 0.15 and 0.80 μ strain at two stations located at 6 and 10 km from the central craters, respectively [Bonaccorso *et al.*, 2013b]. These signals allow us to numerically model the shallow depressurizing source that fed the lava fountains. A grid search procedure indicated that the best source was located at sea level and underwent a volume change of $2 \times 10^6 \text{ m}^3$ [Bonaccorso *et al.*, 2013b] with a pressure change dP of -5 MPa that can be considered the representative of each eruptive episode. The source volume change (ΔV_{source}) represents part of the total erupted volume ($\Delta V_{\text{erupted}}$). Another volume fraction (ΔV_{compr}) can be attributed to magma compressibility C that can accommodate a batch of magma, following the relation :

$$\Delta V_{\text{erupted}} = \Delta V_{\text{source}} + \Delta V_{\text{compr}} \quad (1)$$

To infer the ΔV_{compr} we used the compressibility expression

$$1/C = -V \times \frac{dP}{dV} \quad (2)$$

For the volume of the source, we considered a near spherical source of radius of 0.5 km inferred by strain change [Bonaccorso *et al.*, 2013b] that also matches well with the source position and dimension inferred from the volcanic tremor localizations [Bonaccorso *et al.*, 2011]. Compressibility of bubble-free basaltic magma is in the range $0.4 - 2.0 \times 10^{-10} \text{ Pa}^{-1}$ [Spera, 2000], and in our case we selected the upper limit of this range due to the very shallow location of the source. Under these constraints, $\Delta V_{\text{compr}} = 0.5 \times 10^6 \text{ m}^3$, independently confirming that $2.5 \times 10^6 \text{ m}^3$ is the representative average erupted volume $\Delta V_{\text{erupted}}$ for each lava fountain event, as estimated previously.

The $\Delta V_{\text{erupted}}$ volume is about one order of magnitude greater than the events that occurred in 2000, which produced $\sim 2.5 \times 10^5 \text{ m}^3$ of lava and $\sim 0.3 \times 10^4 \text{ m}^3$ of tephra [Alparone *et al.*, 2003]. Using the representative erupted volume, the total emitted volume for the 38 lava fountain episodes that

took place in 2011-13 is $\sim 95 \times 10^6 \text{ m}^3$.

3. Magma output rate

Wadge and Guest [1981] described the long-term, steady-state magma output displayed by Etna volcano between 1971 and 1981, estimating an average magma output rate of $0.67 \text{ m}^3 \text{ s}^{-1}$ for this period. *Allard et al.* [2006] and *Tanguy et al.* [2007] presented a compilation of Etna's eruptions with the estimation of erupted volumes for both effusive and explosive phases. *Harris et al.* [2011, 2012] have updated this data set to 2010 adding both ground-based and satellite measurements, and have obtained an average output rate of $0.8 \text{ m}^3 \text{ s}^{-1}$ over the three decades between 1980 and 2010.

The estimation of erupted lava flow volumes shows different levels of uncertainties depending on the method used to obtain it. At Etna, we have a wide range of uncertainties, spanning from 20% [*Calvari et al.*, 1994] to 12% [*Stevens et al.*, 1997] obtained on the 1991-93 lava flow field using GPS and EDM field surveys, respectively, to 1.7-6.1% resulting from a precise comparison of the pre- and post-eruption DEMs (digital elevation models) for the 2001 lava flow field [*Coltelli et al.*, 2007]. However, in most cases where lava flow volume is extrapolated from effusion rate measurements, an error up to $\sim 50\%$ is expected [*Harris et al.*, 2007].

In Table 1 we report a collection of Etna's erupted volumes that include both effusive and explosive activity, where we have further extended the published databases by adding the cumulative volumes of lava and pyroclastics estimated for the 38 lava fountaining episodes from January 2011 to April 2013. The graph of the erupted volumes is shown in figure 1, where it is also reported the linear cumulated trend for the expected cumulated volume with the average $0.8 \text{ m}^3 \text{ s}^{-1}$ magma output, estimated from 1980 to 2010. Figure 1 starts with an eruptive pause (horizontal line) following the 1991-93 eruption, which having erupted $\sim 200 \times 10^6 \text{ m}^3$ of magma, has been considered the most voluminous of the last three centuries [*Calvari et al.*, 1994; *Stevens et al.*, 1997]. For this reason, we postulate that at the end of this extremely voluminous eruption the plumbing system was in an

equilibrium state, as also indicated by the successive long eruptive pause and low output rate. It took six years to increase the output rate from $0.1 \text{ m}^3 \text{ s}^{-1}$ recorded in the interval between 1995 and early 1999, during which the summit craters showed an increasing explosive activity, to $2.0 \text{ m}^3 \text{ s}^{-1}$ that characterized the 1999 explosive and effusive phases from the BN and SEC. The 66 paroxysmal episodes in 2000 had an output rate of $1.2 \text{ m}^3 \text{ s}^{-1}$. However, the cumulative discharged volume remained below the equilibrium state traced by the $0.8 \text{ m}^3 \text{ s}^{-1}$ linear trend (Fig. 1). The next effusive eruptions occurred in 2001 and 2002-03, which together with the following 2004-05 and 2006 ones, emitted a cumulative volume approaching the value expected from the equilibrium linear trend. The 7 lava fountain episodes of 2007-08 discharged a modest magma volume of $\sim 10 \times 10^6 \text{ m}^3$ (average output rate of $0.3 \text{ m}^3 \text{ s}^{-1}$) and equilibrium was again reached through the 2008-09 effusive eruption that discharged $68 \times 10^6 \text{ m}^3$ (average output rate of $1.9 \text{ m}^3 \text{ s}^{-1}$). After a 1.5 year eruptive pause, the 38 lava fountains of 2011-13 discharged a huge cumulated volume of $\sim 95 \times 10^6 \text{ m}^3$ with an effective average output rate of $1.4 \text{ m}^3 \text{ s}^{-1}$. Figure 2 shows a magnification of the most recent portion of figure 1, with the details of the cumulative volume considering the representative mean erupted volume of $\sim 2.5 \times 10^6 \text{ m}^3$ for each lava fountain taking place between 2011 and 2013.

4. Discussion

The most hazardous eruptions at Etna are those effusive episodes that involve large lava volumes erupted from the flanks of the volcano that can threaten many towns and infrastructures. A critical topic is the correct assessment of the maximum volume expected from an impending eruption.

The $0.8 \text{ m}^3 \text{ s}^{-1}$ average discharge rate of Etna volcano (i.e. $\sim 25 \times 10^6 \text{ m}^3$ per year) implies that it needs to discharge a large amount of magma through frequent and voluminous eruptions. This is usually achieved every few years through effusive eruptions. This recent trend has now been stable for over 40 years [Harris *et al.*, 2011; 2012].

In this paper we analyzed the effusion rate of the past 20 years following the 1991-93 eruption. This eruption was the largest of the past 3 centuries with $\sim 200 \times 10^6 \text{ m}^3$ of magma erupted over nearly

15 months, and it fully balanced the magma previously accumulated. Therefore, we believe that at the end of this extremely voluminous eruption the plumbing system was in an equilibrium state (the initial zero point in figure 1), and analyze the cumulated volumes erupted from the 1991-93 eruption to the last recent eruptive phase of the January 2011–April 2013 lava fountains. Moreover, after the 1991-93 eruption, for the numerous effusive eruptions and prolonged periods of explosive activity with lava fountains, reliable estimates of the emitted volumes exist. Therefore, the output rates of both eruptive styles (effusive and explosive) are well known. The average output rate of $0.8 \text{ m}^3 \text{ s}^{-1}$ represented in figure 1 shows the expected tendency of the volcano to maintain an equilibrium between magma input and output. We observe that long eruptive pauses or low eruptive rates cause the data trend to move away from the $0.8 \text{ m}^3 \text{ s}^{-1}$ equilibrium line, thus requiring phases of greater magma output or more frequent eruptive events in order to once again establish the original balance.

Unlike effusive eruptions, lava fountains are a different mechanism of magma discharge. Over the past 20 years there have been prolonged periods of lava fountains, such as in 1998 (22 events), 2000 (66 events), 2001 (15 events), 2007-08 (7 events), and recently in 2011-13 (38 events). The first three periods showed a lower average output rate than the expected mean value, and thus failed to discharge all the magma previously accumulated within the storage system. In the fourth case (2007-08), except one particular episode [Andronico *et al.*, 2008], the lava fountains erupted a small magma volume. The trend of figure 1 shows that during these phases the slope of the emitted volume is lower than the $0.8 \text{ m}^3 \text{ s}^{-1}$ expected trend, and thus it moves away from the equilibrium state, and the supply system is accumulating magma. In all these cases the discharge from the lava fountains is not efficient enough to restore the equilibrium, and this is why it is followed by subsequent effusive eruptions that enhance magma discharge. Therefore, in these cases the lava fountain phases, in agreement with previous interpretations [e.g., Behncke and Neri, 2003; Bonaccorso *et al.*, 2011a; Calvari *et al.*, 2011], represent a precursor to effusive eruptions, whose lava flows will tend to balance the influx and efflux of magma.

The last January 2011 – April 2013 phase of lava fountains, where the average output rate was high, is a different situation. This involved a high number of events (38 episodes) of considerable average volume ($\sim 2.5 \times 10^6 \text{ m}^3$), with a total volume of $\sim 95 \times 10^6 \text{ m}^3$ (Fig. 2). Unlike the previous lava fountain phases, these last paroxysmal events contributed to approaching the equilibrium trend with an $\sim 1.4 \text{ m}^3 \text{ s}^{-1}$ average output rate during a 16 months period,. Therefore, in the specific case of the January 2011- April 2013 phase, the repeated lava fountains represent a very efficient way of magma discharge, which would not imply an imminent further effusive eruption to obtain a balance between the incoming and outgoing magma. In this frame, the lava fountains do not represent a precursor of major effusive events. They are instead a powerful discharge mechanism that effectively favors the equilibrium of the volcano supply system by enhancing the output of the stored magma (Fig. 2).

In our work we make a step forward in interpreting the recent lava fountain activity and estimating the expected volumes that will be erupted to reach equilibrium again. As an example, a six-month long eruptive pause (at the time of writing) results in accumulation of $\sim 12 \times 10^6 \text{ m}^3$ magma in the feeding system, that can be released by several new lava fountain episodes or by a short-lasting effusive event. Nevertheless, we cannot exclude that in the future another major flank eruption will occur, of the same size as the 1991-93 event, falling outside the typical -and expected- output rate of the volcano. However, these events are extremely rare at Etna, as can be argued by the fact that this eruption size occurred just once in three centuries, and instead for countless other eruption cases the expected linear law was well followed. Our model can just reveal the size of the magma volume, accumulated within the volcanic system, and that is waiting to be erupted. Major earthquakes, a greater sliding of the eastern flank, or a greater supply from the source region could cause significant and unexpected departures from the average output trend, with unpredictable effects.

5. Concluding remarks

The evaluation of erupted volumes at volcanoes characterized by a steady average magma output rate allows us to infer their future behavior. At Etna, we have observed that pauses of eruptive activity or low output rates cause the eruption trend to move away from the interpolated average equilibrium value of $0.8 \text{ m}^3 \text{ s}^{-1}$, thus requiring a successive phase with greater magma output, normally resulting in major effusive eruptions. The lava fountain episodes occurring at Etna between 1998 and 2008 did not erupt significant volumes of magma, and were then followed by major effusive eruptions to restore the equilibrium. In contrast, we have highlighted that the multiple explosive episodes that have recently characterized the volcano from January 2011 to April 2013, having efficiently drained the storage system, do not herald imminent large effusive eruptions. Instead, they represent a different and efficient way of releasing the magma stored within the supply system. Thus, if the average output rate of the volcano remains steady during the next decades, and if the erupted volumes (both lava flows and pyroclastics) are regularly estimated, then we should be able to detect the phases when the balance between intruded and erupted magma is moving away from equilibrium, becoming more prone to major eruptions. The proposed interpretation allows suggesting, for a given time frame, the volume that an on-going eruptive activity (i.e., main effusive eruption or lava fountain episodes) will emit to reach the equilibrium or that will be erupted by a potential new eruptive activity starting at that time. Thus, at the time of writing, after an eruptive pause of nearly 6 months during which $\sim 12 \times 10^6 \text{ m}^3$ of magma have been accumulated within the system, we can expect either a few lava fountain episodes or a short-lasting effusive phase to restore the equilibrium of the system.

Acknowledgements

We are grateful to two anonymous referees and the Associated Editor who helped us to significantly improve an earlier version of the manuscript, and two anonymous referees who contributed to improve this paper. We thank Stephen Conway for revising the English language of this manuscript. We thank Veronica Testa for having authorized us to use her photo in figure 2.

References

- Allard, P., B. Behncke, S. D'Amico, M. Neri, and S. Gambino (2006), Mount Etna 1993–2005: Anatomy of an evolving eruptive cycle, *Earth Sci. Rev.*, **78**, 85–114, doi:10.1016/j.earscirev.2006.04.002.
- Alparone, S., D. Andronico, L. Lodato, and T. Sgroi (2003), Relationship between tremor and volcanic activity during the Southeast Crater eruption on Mount Etna in early 2000, *J. Geophys. Res.*, **108**(B5), 2241, doi:10.1029/2002JB001866.
- Andronico, D., S. Branca, S. Calvari, M.R. Burton, T. Caltabiano, R.A. Corsaro, P. Del Carlo, G. Garfi, L. Lodato, L. Miraglia, F. Muré, M. Neri, E. Pecora, M. Pompilio, G. Salerno, and L. Spampinato (2005), A multi-disciplinary study of the 2002-03 Etna eruption: insights for into a complex plumbing system, *Bull. Volcanol.*, **67**, 314-330, doi:10.1007/s00445-004-0372-8.
- Andronico, D., and R.A. Corsaro (2011), Lava fountains during the episodic eruption of South–East Crater (Mt. Etna), 2000: insights into magma-gas dynamics within the shallow volcano plumbing system, *Bull. Volcanol.*, **73**, 1165-1178, doi: 10.1007/s00445-011-0467-y.
- Andronico, D., A. Cristaldi, and S. Scollo (2008), The 4–5 September 2007 lava fountain at South-East Crater of Mt Etna, Italy, *J. Volcanol. Geoth. Res.*, **173**, 325-328, doi: 10.1016/j.jvolgeores.2008.02.004.
- Behncke, B., and M. Neri (2003), The July–August 2001 eruption of Mt. Etna (Sicily), *Bull. Volcanol.*, **65**, 461–476, doi:10.1007/s00445-003-0274-1.
- Behncke, B., S. Branca, A.R. Corsaro, E. De Beni, L. Miraglia, C. Proietti (2012), The 2011-12 summit activity of Etna : growth of the new SE crater and petrochemistry of the products, *Miscellanea INGV*, ISSN 2039-665, n. 15, 24.
- Bonaccorso, A., A. Bonforte, S. Calvari, C. Del Negro, G. Di Grazia, G. Ganci, M. Neri, A. Vicari, and E. Boschi (2011a), The initial phases of the 2008–2009 Mount Etna eruption: A multidisciplinary approach for hazard assessment, *J. Geophys. Res.*, **116**, B03203,

doi:10.1029/2010JB007906.

- Bonaccorso A., T. Caltabiano, G. Currenti, C. Del Negro, S. Gambino, G. Ganci, S. Giammanco, F. Greco, A. Pistorio, G. Salerno, S. Spampinato and E. Boschi (2011b), Dynamics of a lava fountain revealed by geophysical, geochemical and thermal satellite measurements: the case of the 10 April 2011 Mt Etna eruption, *Geophys. Res. Lett.*, doi:10.1029/2011GL049637
- Bonaccorso, A., S. Calvari, G. Currenti, C. Del Negro, G. Ganci, A. Linde, R. Napoli, S. Sacks, and A. Sicali (2013a), From Source to Surface: Dynamics of Etna's Lava Fountains Investigated by Continuous Strain, Magnetic, Ground and Satellite Thermal Data, *Bull. Volcanol.*, *75*, 690, doi:10.1007/s00445-013-0690-9.
- Bonaccorso, A., G. Currenti, A. Linde, S. Sacks (2013b), New data from borehole strainmeters to infer lava fountain sources (Etna 2011-2012), *Geophys. Res. Lett.*, *40*, 1-6, doi:10.1029/2013GL050692.
- Calvari, S., and the whole scientific staff of INGV – Sezione di Catania (2001), Multidisciplinary Approach Yields Insight into Mt. Etna 2001 Eruption, *EOS Transactions, AGU*, *82*, 52, 653-656.
- Calvari, S., M. Coltelli, M. Neri, M. Pompilio, and V. Scribano (1994), The 1991-93 Etna eruption: chronology and lava flow field evolution, *Acta Vulcanol.*, *4*, 1-14.
- Calvari, S., M. Neri, and H. Pinkerton (2003), Effusion rate estimations during the 1999 summit eruption on Mt. Etna, and growth of two distinct lava flow fields, *J. Volcanol. Geoth. Res.*, *119*, 107-123, doi:S0377-0273(02)00308-6, ISSN0377-0273.
- Calvari, S., G. G. Salerno, L. Spampinato, M. Gouhier, A. La Spina, E. Pecora, A. J. L. Harris, P. Labazuy, E. Biale, and E. Boschi (2011), An unloading foam model to constrain Etna's 11–13 January 2011 lava fountaining episode, *J. Geophys. Res.*, *116*, B11207, doi:10.1029/2011JB008407.
- Coltelli, M., C. Proietti, S. Branca, M. Marsella, D. Andronico, and L. Lodato (2007), Analysis of the 2001 lava flow eruption of Mt. Etna from three-dimensional mapping. *J. Geophys. Res.*, *112*, F02029, doi:10.1029/2006JF000598.

- Ganci, G., A. J. L. Harris, C. Del Negro, Y. Guéhenneux, A. Cappello, P. Labazuy, S. Calvari, and M. Gouhier (2012), A year of lava fountaining at Etna: volumes from SEVIRI, *Geophys. Res. Lett.*, **39**, L06305, doi:10.1029/2012GL051026.
- Gouhier, M., A. J. L. Harris, S. Calvari, P. Labazuy, Y. Guéhenneux, F. Donnadieu, and S. Valade (2012), Lava discharge during Etna's January 2011 fire fountain tracked using MSG-SEVIRI, *Bull. Volcanol.*, **74**, 787–793, doi: 10.1007/s00445-011-0572-y.
- Harris, A.J.L., J. Dehn, and S. Calvari (2007), Lava effusion rate definition and measurement: a review. *Bull. Volcanol.*, **70**, 1–22, doi:10.1007/s00445-007-0120-y.
- Harris, A. J. L., and M. Neri (2002), Volumetric observations during paroxysmal eruptions at Mount Etna: pressurized drainage of a shallow chamber or pulsed supply? *J. Volcanol. Geoth. Res.*, **116**, 79-95, doi:10.1016/S0377-0273(02)00212-3.
- Harris, A.J.L., A. Steffke, S. Calvari, and L. Spampinato (2011), Thirty years of satellite-derived lava discharge rates at Etna: Implications for steady volumetric output, *J. Geophys. Res.*, **116**, B08204, doi: 10.1029/2011JB008237.
- Harris, A.J.L., A. Steffke, S. Calvari, and L. Spampinato (2012), Correction to “Thirty years of satellite-derived lava discharge rates at Etna: Implications for steady volumetric output”. *J. Geophys. Res.*, **117**, B08207, doi:10.1029/2012JB009431.
- Spera, F. (2000), Physical properties of magma, in Sigurdsson, H., Houghton, B., McNutt, B., Rymer, H., and Stix, J., eds, *Encyclopedia of volcanoes*, pp. 171-190, Academic Press, San Diego, California
- Stevens, N.F., J.B. Murray, and G. Wadge, (1997), The volume and shape of the 1991-1993 lava flow field at Mount Etna, Sicily, *Bull. Volcanol.*, **58**, 449–454.
- Tanguy, J.C., M. Condomines, M. Le Goff, V. Chillemi, S. La Delfa, and G. Patané (2007), Mount Etna eruptions of the last 2,750 years: revised chronology and location through archeomagnetic and ²²⁶Ra-²³⁰Th dating, *Bull. Volcanol.*, **70**, 55-83, doi: 10.1007/s00445-007-0121-x.
- Wadge, G., and J. E. Guest (1981), Steady-state magma discharge at Etna 1971–81, *Nature*, **294**,

Accepted Article

Table 1. Volumes and mean output rates for Etna's eruptive activity during the period 1993-2013. Magma volumes of effusive-explosive activity comprise pyroclastics and lava flows. (*) Mean value from *Allard et al.* [2006] and *Tanguy et al.* [2007]; (**) from *Harris et al.* [2011, 2012]. (***) the 2007 lava fountains volumes have been extrapolated using data from *Andronico et al.* [2008] for the most intense event of 4-5 September, whereas the other 6 smaller events are accounted for using the volume from *Bonaccorso et al.* [2011a]; (****) this study. The summit craters of the volcano are identified by BN = Bocca Nuova; NEC = North-East Crater; SEC = South-East Crater; VOR = Voragine Crater. The estimated error associated with the erupted volume is discussed in the text.

Period	Activity	From (dd/mm/yyyy)	To (dd/mm/yyyy)	Magma volume (m ³)	Magma output rate (m ³ s ⁻¹)	
1) 1993-95	Eruptive pause after the end of the main 1991-93 eruption.	01/04/1993	01/06/1995	0	0	
2) 1995-99	Increasing summit activity. Strombolian activity at BN, and lava fountain episodes. NEC: 10 lava fountain episodes (Aug. 1995 - Aug. 1996). SEC: strombolian activity and lava overflow (Nov. 1996 – July 1998). VOR: strong explosive activity (May - Sept. 1998) and minor lava emission. SEC: 23 small lava fountains and lava overflow (Sept. 1998 – 4 Febr. 1999).	01/06/1995	04/02/1999	16.0	0.1	*
3) 1999	Summit effusive eruption (4 Febr. - 5 Nov. 1999). BN: (4 Sept. – 5 Nov.) several episodes of lava fountains, extensive lava flows. VOR: strong explosive activity (June – Oct. 1999).	04/02/1999	10/11/1999	47.0	2.0	*
4) 2000	SEC: (Jan. – Aug. 2000) 66 lava fountains eruptive episodes with lava flows. SEC: (2001) strombolian activity, 16 lava fountain eruptive episodes with extensive lava flows.	26/01/2000	17/07/2001	58.5	1.2	*
5) 2001	July – Aug. 2001: flank eruption, effusive and explosive activity.	17/07/2001	10/08/2001	30.0	15.4	*
6) 2002-03	Flank eruption, effusive and explosive activity.	26/10/2002	29/01/2003	57.5	7.4	*
7) 2004-05	Effusive flank eruption.	07/09/2004	08/03/2005	64.0	4.1	**
8) 2006	Effusive flank eruption.	14/07/2006	15/12/2006	39.0	3.0	**
9) 2007-08	7 lava fountains from SEC.	29/03/2007	10/05/2008	10.0	0.3	***
10) 2008-09	Effusive flank eruption with initial lava fountain.	13/05/2008	07/07/2009	68.0	1.9	**
11) 2011-13	38 lava fountains from SEC.	10/01/2011	27/04/2013	95	1.4	****

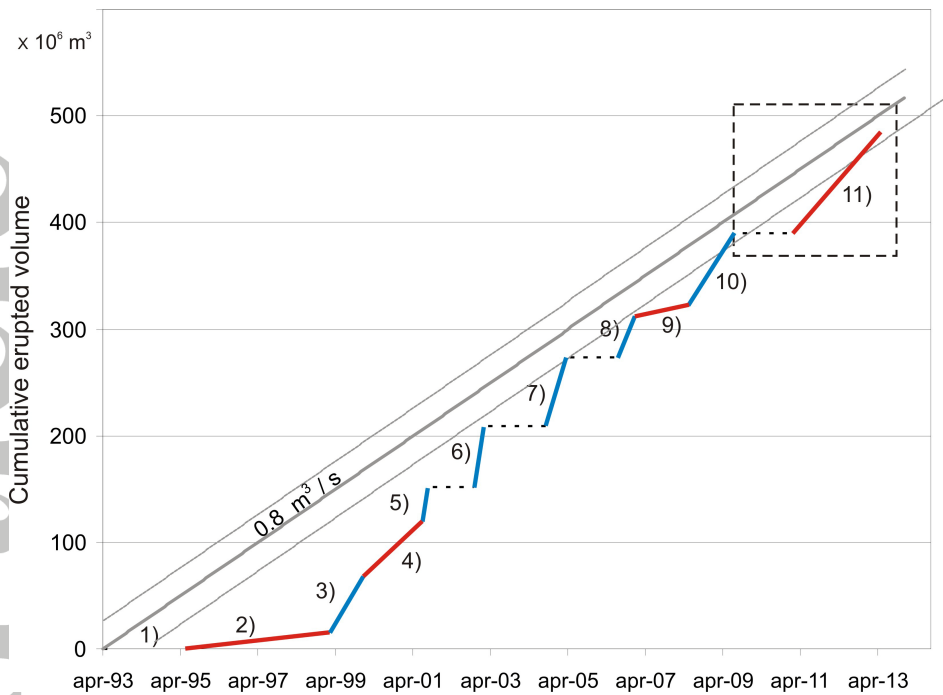


Figure 1. The cumulative volume erupted from Etna between April 1993 and April 2013. The corresponding values are reported in Table 1. We assume that at the end of the December 1991 to March 1993 eruption ($\sim 200 \times 10^6 \text{ m}^3$ of erupted magma) the plumbing system was in equilibrium state. Red lines indicate the volumes erupted by the lava fountains, blue lines indicate the effusive eruptions. The grey line is the average output rate of $0.8 \text{ m}^3 \text{ s}^{-1}$ calculated over the three decades between 1980 and 2010 [Harris *et al.*, 2011, 2012]. The dashed lines represent the standard deviation ($\pm 25 \times 10^6 \text{ m}^3$) from the data of Harris *et al.* (2011). The dashed square comprises the period with the last 38 lava fountaining events occurring at Etna volcano between January 2011 and April 2013. A magnification of this most recent portion is detailed in figure 2.

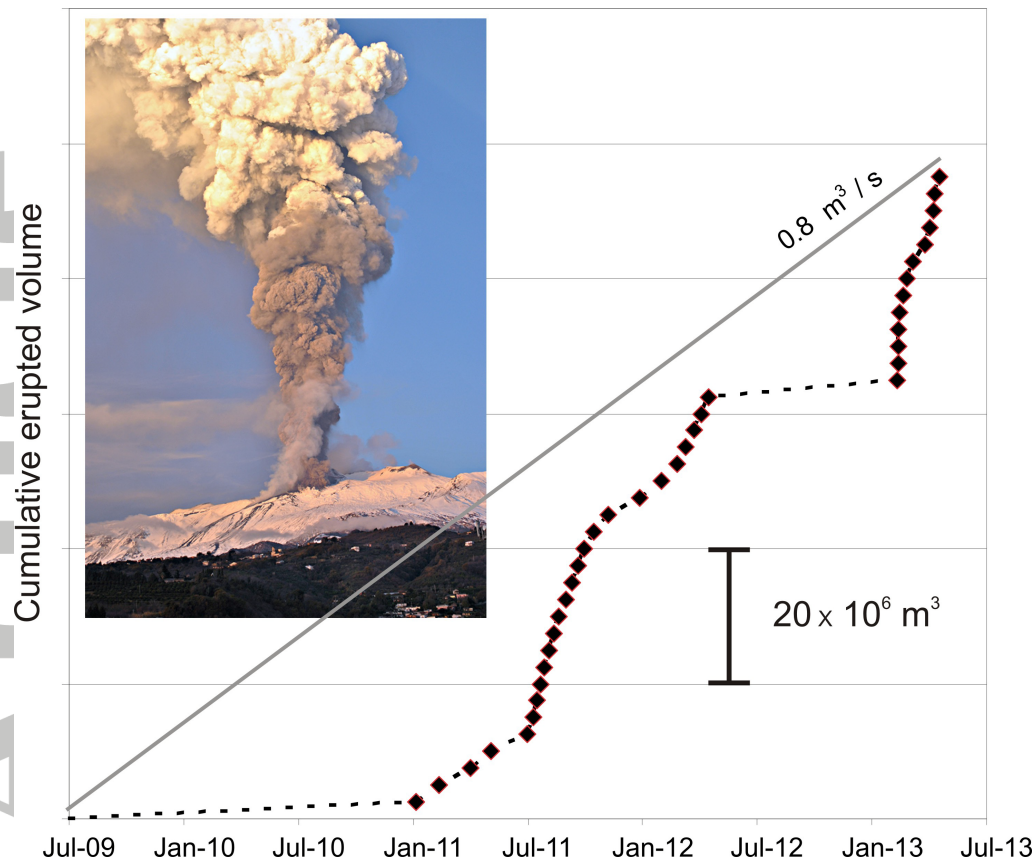


Figure 2. Graph showing the cumulative erupted volume (lava flows plus pyroclastics) of the 38 lava fountaining events that took place at Etna volcano between January 2011 and April 2013. The cumulative volume is obtained by considering for each lava fountain the representative mean erupted volume of $\sim 2.5 \times 10^6 \text{ m}^3$. The dashed grey line is the average output rate of $0.8 \text{ m}^3 \text{ s}^{-1}$ calculated over the three decades from 1980 to 2010 [Harris *et al.*, 2011, 2012]. The photo in the inset shows the 5 January 2012 lava fountain episode taken from the E flank of Etna, displaying a well developed eruptive column $\sim 6 \text{ km}$ high. At its base, the lava flow flowing eastward (left) and covering the previous lava flow field (in black). All the 38 lava fountain episodes occurring from January 2011 to April 2013 showed similar main characteristics. Photo courtesy of Veronica Testa.